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AN EXPERIMENTAL STUDY OF THE EFFECTS OF WATER REPELLANT TREATMENT ON THE ACOUSTICS PROPERTIES OF KEVLAR

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AN EXPERIMENTAL STUDY OF THE EFFECTS OF WATER REPELLENT TREATMENT ON ACOUSTIC PROPERTIES OF KEVLAR

BY

C. D. Smith* and T. L. Parrott

SUMMARY

Tests were conducted to determine the effects of water repellent treatment on the acoustic and physical properties of Kevlar (type 1299, style 29). The treatment consisted of immersing samples of Kevlar in a solution of distilled water and Zepel (TLF 2325). The samples were then drained, dried in a circulating oven, and cured.

Flow resistance tests showed approximately one percent decrease in flow resistance of the samples. Also there was a density increase of about three percent. It was found that the treatment caused a change in the texture of the samples.

There were significant changes in the acoustic properties of the treated Kevlar over the frequency range 0.5 to 3.5 kHz. In general it was found that the propagation constant and characteristic impedance increased with the increasing frequency. However, the real and imaginary components of the propagation constant for the treated Kevlar exhibited a decrease of 8 to 12 percent relative to that for the untreated Kevlar at the higher frequencies. The magnitude of the reactance component of the characteristic impedance decreased by about 40 percent at the higher frequencies.

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INTRODUCTION

The demand for lower noise levels radiated from jet aircraft engines has motivated research to discover appropriate materials to use as duct liners. (See reference 1). It is well known that bulk materials such as fiberglass and open-celled foams are good absorbers of broadband noise. Acceptance of bulk materials as duct liners requires that the material be able to withstand the adverse environmental conditions that exist within the inlets. (See reference 2). One of these conditions is the contamination of the material by such fluids as fuel, cleaning solvents, and rain. The absorption of these fluids by the material has two detrimental effects: (1) an increase in the weight of the liners resulting in a reduction in the power/weight ratio of the jet engines; and (2) alterations in the acoustic properties of the material which may result in potentially decreasing the acoustic performance of the liner.

The acoustic performance of bulk materials is determined by two fundamental acoustic properties. These properties are called the propagation constant and the characteristic impedance. The propagation constant is a complex number describing the propagation of a sound wave through the material. The real component, called the attenuation constant, describes the rate of sound absorption within the material. The imaginary component, called the phase constant, is related to the speed of sound in the material. The characteristic impedance is defined as the ratio of acoustic pressure to acoustic particle velocity for a progressive wave in the material.

The purpose of these tests was to evaluate the change in physical and acoustic properties of one type Kevlar (produced by the DuPont Company) when treated with a fluid repellent. The Kevlar chosen for these tests

(type 1299, style 29) is a strong, lightweight porous material made of synthetic fibers. The particular test samples used in this investigation were taken from a blanket approximately 1 cm thick. The fluid repellent used in the test was a fluorocarbon produced by Dupont (Zepel TLF 2324). The acoustic properties of the treated and untreated samples of Kevlar were determined using the impedance tube method as described in references 3 and 4. Specifically the two-cavity technique was used to determine the propagation constant and characteristic impedance from surface impedance measurements. (See reference 5). Changes in the density and specific flow resistance of the samples were also determined.

SYMBOLS

c	free space sound speed, cm/sec
d	length of test specimen, cm
k	acoustic wave number, cm^{-1}
p	pressure, $gm\ cm^{-1}\ sec^{-2}$
ΔP	pressure drop across specimen
R	acoustic resistance, cgs rayls ($gm\ cm^{-1}\ sec^{-2}$)
R_c	characteristic resistance, cgs rayls
$\lvert R_f \rvert_o$	reflection factor magnitude at test specimen surface
R_{sf}	specific flow resistance, $gm\ cm^{-2}\ sec^{-1}$
S_o	standing wave ratio, dB
v	air velocity, $cm\ sec^{-1}$
X_1	distance to first null, cm
Z	acoustic impedance, cgs rayls
Z_c	characteristic impedance, cgs rayls
Z_1	acoustic impedance with quarter wavelength cavity depth cgs rayls
Z_2	acoustic impedance with zero cavity depth acoustic termination cgs rayls

α	attenuation constant, nepers cm^{-1} or dB cm^{-1}
β	phase constant, rad cm^{-1}
γ	propagation constant, $\gamma = \alpha + j\beta$, cm^{-1}
λ	wavelength, cm
χ	acoustic reactance, cgs rayls
χ_c	characteristic reactance, cgs rayls
ρ	density of air, gm cm^{-3}
σ_α	standard deviation of the attenuation constant, dB cm^{-1}
σ_β	standard deviation of the phase constant, rad cm^{-1}
σ_{R_c}	percent standard deviation from the mean of the characteristic resistance (normalized to ρc)
σ_{χ_c}	percent standard deviation from the mean of the characteristic reactance (normalized to ρc)

THEORETICAL CONSIDERATIONS

Determination of the propagation constant, γ, and characteristic impedance, Z_c, of bulk materials using the two-cavity method requires the measurement of the acoustic impedance at the surface of a finite length of the material backed by two different acoustic terminations. Figure 1 shows a schematic diagram of a plane wave impinging normally on the surface of a test specimen of length d and backed by a rigid walled cavity of adjustable length ℓ-d. It is convenient to have one of the terminations present zero impedance to the rear surface of the specimen. This is accomplished by setting the cavity depth to a quarter wavelength i.e. ($\ell - d = \frac{\lambda}{4}$). The acoustic impedance, Z_1, at the front surface of the

test specimen is given by

$$Z_1 = Z_c \tanh (\gamma d) \tag{1}$$

where Z_c is the characteristic impedance of the material. It is convenient to choose the second termination to provide an infinite impedance to the rear surface of the test specimen. This is provided by making the cavity depth zero i.e. (ℓ-d = 0). The acoustic impedance, Z_2, at the front surface of the test specimen is given by

$$Z_2 = Z_c \coth (\gamma d) \tag{2}$$

Equations (1) and (2) are easily solved for γ and Z_c in terms of the measured impedance Z_1 and Z_2 as follows:

$$\gamma = \frac{1}{d} \quad \ell n \left[\frac{1 + y}{1 - y}\right] \tag{3}$$

where

$$y = \left[\frac{Z_1}{Z_2}\right]^{1/2} \quad \text{and}$$

$$Z_c = \left[Z_1 \quad Z_2\right]^{1/2} \tag{4}$$

The propagation constant and characteristic impedance expressed in terms of their respective components are

$$\gamma = \alpha + j\beta \tag{5}$$

and

$$Z_c = R_c + jX_c.$$

The attenuation constant can be conveniently expressed in dB/cm by multiplying α by 8.68. (See reference 3).

EXPERIMENTAL APPARATUS AND PROCEDURES

Impedance Tube Apparatus

A block diagram of the impedance tube and associated instrumentation is shown in Figure 2. The apparatus consists of a main cylindrical tube section in which a test specimen is mounted at one end by means of a test specimen fixture. A variable cavity backing depth is provided by a movable piston in the test specimen fixture as shown in the sketch. The movable piston is fitted with O-rings at each end to provide an airtight sliding contact with the machined inside surface of the cavity backing tube. The main tube has an inside diameter of 5.715 cm (2.25 in.), a wall thickness of 0.645 cm (0.25 in.) and a length of 83.83 cm (33 in.). A sound source consisting of a 60-Watt electromagnetic driver was coupled to the main tube through an offset exponential horn as shown in the sketch. A flexible coupling was used to decouple the mechanical vibrations of the driver from the walls of the tube. A further precaution was taken to reduce the mechanical vibrations from the tube walls by wrapping two layers of asphalt-based damping tape over the entire length of the tubes. The test specimen fixture was fabricated to allow the insertion of aluminum rings with an outside diameter of 5.233 cm (2.45 in.) and a wall thickness of 0.26 cm which (0.1 in.) were used to contain the specimens.

Acoustic Pressure Transducer and Associated Hardware

Acoustic signals were monitored simultaneously using the two condenser type microphone as shown in Figure 2. A 0.64 cm (0.25 in.) diameter

microphone (mic one) was used to measure the acoustic pressure level at the piston face. A 1.27 cm (0.5 in.) microphone (mic two) was coupled to a steel probe tube O.D. = 0.32 cm (0.125 in.), I.D. = 0.19 cm (0.075 in.) and a length of 122 cm (48 in.) to obtain relative acoustic pressure level measurements at points on the axis of the main tube. Microphone 2 was isolated mechanically from the probe tube and tube support hardware. Fixed positions for both the axial probe and the piston position could be determined to within $\pm$ 0.01 cm with the use of specially constructed verniers.

Electronic Instrumentation

A block diagram of the electronic instrumentation used in this test is also shown in Figure 2. To measure the impedance of the specimens using the standing wave method, the acoustic pressure at the specimen surface was maintained at a constant level by monitoring the output of microphone 2 connected to the probe. The signals from both microphones were filtered using a dual channel 10 Hz bandwidth tracking filter whose center frequency was automatically set by the oscillator frequency used to drive the acoustic source. A spectrum analyzer was used to monitor the overall spectrum content of the signal at the piston face in order to detect malfunctions of equipment, excessive background noise or nonlinear behavior of the acoustic source. In this manner, the harmonic content of the excitation acoustic pressure was maintained well below the levels of its fundamental frequency. The tracking filter outputs were read out on a dual channel log-volt meter from which the acoustic pressure levels were read consistently to within 0.1 dB.

Flow Resistance Apparatus

Figure 3 shows a block diagram of the apparatus and associated instrumentation used to determine the specific flow resistance of the test specimens.

The apparatus consists of a cylindrical brass tube with I.D. = 5.72 cm (2.25 in.) and a length of 60.96 cm (24 in.) which couples a laminar flow meter to the test specimen fixture. The air flow was controlled by a needle valve and pressure regulator with which accurate control of the volume flow was maintained. The pressure drops across the flow meter and the test specimens were measured using 10 Torr pressure barocels the output of which were displayed on a digital electronic manometer.

Test Specimens

The acoustic and flow resistance tests were performed on five test specimens taken from different sections of a large sheet of Kevlar. The samples were circular in shape with a diameter of 5.72 cm (2.25 in.) to allow them to fit into the aluminum rings. The length of all five specimens was 1 cm.

Acoustic Measurements

The acoustic impedance of the specimens was determined by investigating the standing wave pattern inside the impedance tube caused by the reflection of plane waves at the surface of a specimen. From impedance tube theory (refs. 3 & 4), the impedance is determined by measuring the nondimensional distance to the first null, kx_1 and the reflection factor magnitude at the surface of the test specimen, $|R_f|_0$. These quantities are substituted into the following equations to obtain the components of the acoustic impedance normalized by ρc i.e.

$$\frac{Z}{\rho c} = \theta + j\chi$$

where the resistance ratio θ and reactance ratio χ are given respectively by

$$\theta = \frac{r_o\,[1 + \tan^2\ (kx_1)]}{1 + r_o^2\ \tan^2\ (kx_1)} \tag{7}$$

$$X = \frac{(1 - r_o^2)\ \tan\ (kx_1)}{1 + r_o^2\ \tan^2\ (kx1)} \tag{8}$$

and where

$$r_o = \frac{1 + |R_f|_o}{1 - |R_f|_o}\ .\quad \text{and} \quad |R_f|_o = \frac{10^{S_o/20} - 1}{10^{S_o/20} + 1} \tag{9}$$

Flow Resistance

The specific resistance of the test specimens were determined from

$$R_{sf} = \frac{\Delta P}{Vd}$$

where ΔP is the pressure drop across the sample, V is the approach velocity of the air entering the specimen and d is the specimen length. The air velocity was varied in a systematic manner from 1 to 10 cm/sec. It was found that the flow resistance was constant within experimental error over the range of velocities tested. Therefore, the values given in Table I were taken at a nominal velocity of 1 cm/sec.

Repellent Treatment

The fluid repellent treatment consisted of immersing the test specimens in a solution containing 280 ml of distilled water and 5 ml of Zepel. They were held in the solution at a 28-inch vacuum for five minutes before being removed and drained. The test specimen were dried in a circulating oven at 250°F for 3 hours. After drying, they were cured at 350°F for 15 minutes.

RESULTS AND DISCUSSION

Density and Flow Resistance Changes

Table 1 shows the density and specific flow resistances of the individual test specimens before and after the treatment. The treated specimens showed an average increase in density of about 3.4 percent. The table also shows that there was about a 1 percent decrease in the average specific flow resistances of the 5 test specimens. There was also a detectable change in the texture of the materials. The fibers of the treated samples seemed to be somewhat more rigidly fixed relative to one another than in the case of the untreated samples.

Acoustic Properties

The propagation constant and characteristic impedance were determined for each of the 5 test specimens before and after the treatment. The mean values of the components of γ, and z_c (normalized to ρc) for the 5 test specimens are plotted against frequency as shown in Figures 4 to 7. The circles represent the data for the untreated specimens and the squares show the results for treated specimens. In all four figures, there is a sharp decrease in the components at 700 to 800 Hz. This irregularity in the data may be due to motion of the test specimen fibers. The figures show that there is little change in the acoustic data at low frequencies. However, as frequency increases, the acoustic data for the treated samples begin to diverge from the data for untreated specimens. This divergence is most pronounced in the components of the propagation constant. At 3500 Hz, there is an 8 percent decrease in the attenuation constant and a 12 percent decrease in the phase constant after the water repellent treatment.

Figure 6 shows the characteristic resistance, which is normalized to ρc, to be the least affected of the four acoustic parameters.

The percent standard deviations from the mean (hereafter called relative standard deviation) of the components of γ and z_c (normalized) were computed based on the measurements performed for the five test specimens. The results are shown in Table 2. The table shows that relative standard deviations below 1.0 kHz were large in some cases particularly for 0.7, 0.8, and 0.9 kHz. Above 1.0 kHz, however, the relative standard deviations rarely exceed 5 percent. The large values at the frequencies mentioned suggest that the acoustic wave is causing forced vibratory motion of the material matrix structure with attendant material damping. Also, comparison of relative standard deviations before and after treatment suggests that Kevlar retains its homogeneity when treated with Zepel fluid repellent according to the procedure described previously.

CONCLUSIONS

Tests were performed on Kevlar to determine the effects of a water repellent treatment on its acoustic and nonacoustic properties. An examination of the results of the experiments led to the following conclusions:

1. The specific flow resistance of Kevlar remained unchanged while the weight showed an increase of three percent. The treatment caused a detectable increase in the texture of the material.
2. The effects of the treatment on the acoustic properties were found to be frequency dependent and increasingly significant with increasing frequency. The propagation constant was most affected by the treatment.
3. Kevlar maintained its homogeneity after the treatment.

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TABLE I.

COMPARISON OF PHYSICAL PROPERTIES OF TREATED AND UNTREATED KEVLAR

Specimen Number	UNTREATED KEVLAR		TREATED KEVLAR	
	Density gms/cm³	R_{sf}	Density gm/cm³	R_{sf}
1	.089	79.4	.092	78.9
2	.088	79.8	.092	79.1
3	.089	78.9	.091	78.5
4	.089	79.7	.090	78.7
5	.090	79.1	.093	78.0
Means	.089	79.4	.092	78.6

TABLE 2: PERCENT STANDARD DEVIATIONS FROM THE MEAN VALUES OF Υ AND Z_c

FREQ	UNTREATED				TREATED				
(KHz)	σ_α	σ_β	σ_{R_c}	σ_{X_c}	σ_α	σ_β	σ_{R_c}	σ_{X_c}	
0.5	3.51	6.00	6.97	3.34	7.36	4.24	2.51	9.04	
0.6	2.04	12.66	12.10	2.48	6.95	2.33	2.49	6.44	
0.7	33.25	7.72	11.83	38.03	5.45	10.10	4.62	4.70	
0.8	35.66	33.97	23.49	57.20	19.44	12.31	9.35	29.06	
0.9	11.54	3.77	2.96	15.50	3.19	9.78	3.07	5.73	
1.0	4.65	2.34	4.55	5.77	2.00	6.21	1.90	4.57	
1.1	4.06	2.99	4.71	5.76	2.77	6.85	2.19	2.91	
1.2	4.31	2.96	4.71	5.89	2.94	7.11	2.04	2.53	
1.3	3.70	3.32	4.92	6.22	3.06	5.71	1.74	2.83	
1.4	3.97	3.08	4.52	6.09	3.14	4.93	1.51	2.84	
1.5	2.88	3.33	3.77	6.66	2.45	4.74	1.05	2.91	
1.6	3.25	3.13	4.05	6.97	1.91	4.07	1.39	3.02	
1.7	2.90	3.42	3.88	7.43	1.83	3.96	1.30	3.16	
1.8	2.81	3.19	3.98	7.43	1.81	3.81	1.28	3.10	
1.9	2.33	3.22	3.92	7.37	2.06	3.87	1.37	3.20	
2.0	2.82	3.62	3.91	8.06	2.20	4.12	1.80	3.50	
2.1	2.01	3.26	3.91	7.07	2.40	3.81	1.36	11.56	
2.2	3.41	3.27	4.03	7.57	3.51	4.56	1.20	3.66	
2.3	3.35	2.70	3.56	6.70	2.50	4.82	1.17	4.18	
2.4	2.07	2.71	3.22	6.85	2.61	4.38	1.31	4.48	
2.5	1.67	2.39	3.26	6.26	2.51	3.36	1.35	4.07	
2.6	2.15	3.11	3.16	7.35	2.44	3.48	1.50	4.17	
2.7	2.25	2.81	2.89	8.10	2.15	3.50	1.55	4.84	
2.8	2.37	2.63	2.12	8.96	2.52	3.08	2.05	4.78	
2.9	1.68	2.51	2.20	8.44	2.40	2.91	1.41	5.12	

TABLE 2: CONTINUED

FREQ	UNTREATED				TREATED				
(MHz)	σ_α	σ_β	σ_{P_2}	σ_{X_e}	σ_α	σ_β	σ_{P_2}	σ_{X_e}	
3.0	2.48	2.72	1.86	9.02	2.29	2.61	1.32	6.02	
3.1	2.59	2.61	1.63	8.59	2.78	2.68	1.37	5.44	
3.2	2.38	2.34	1.65	7.67	2.67	2.51	1.49	5.35	
3.3	2.17	2.40	1.56	8.88	2.41	2.75	1.53	5.72	
3.4	2.35	2.19	1.50	10.05	2.07	2.56	1.53	5.61	
3.5	2.50	2.24	1.44	9.72	1.68	2.43	1.51	3.55	

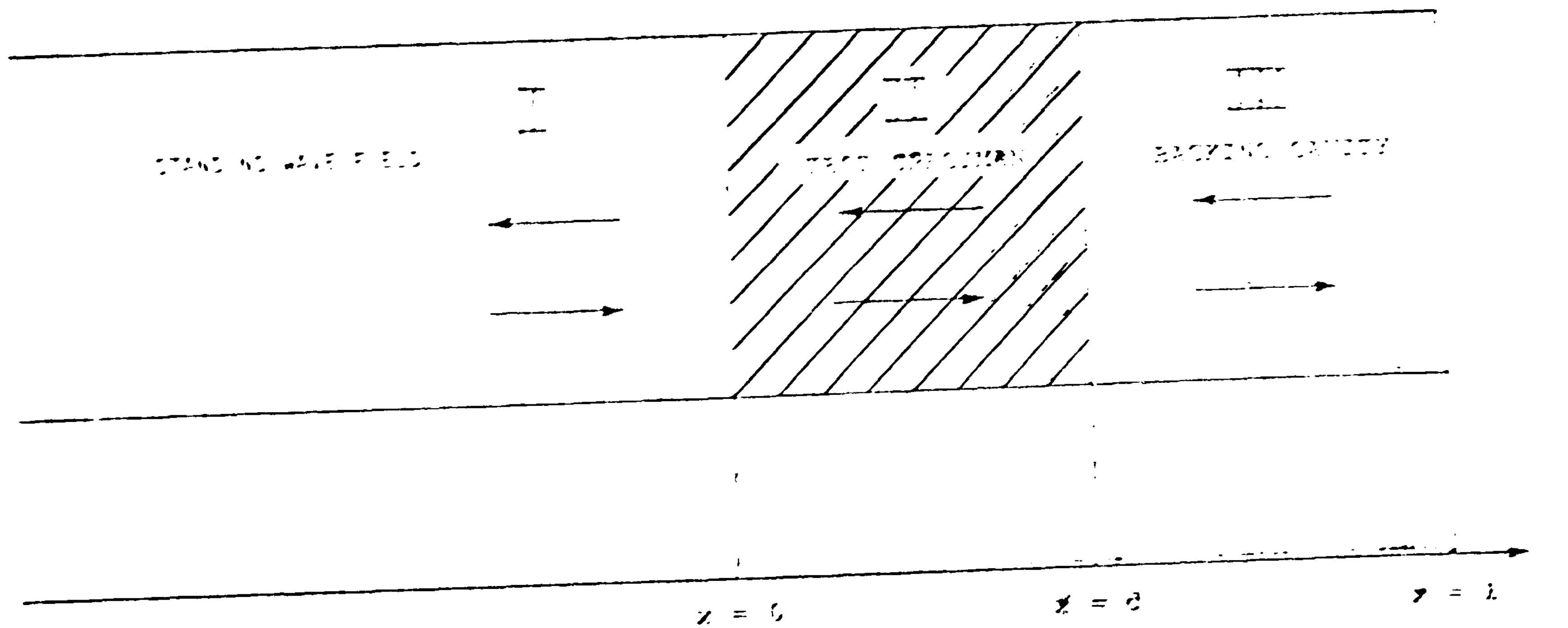

Figure 1. Schematic diagram of impedance tube with test specimen backed by cavity.

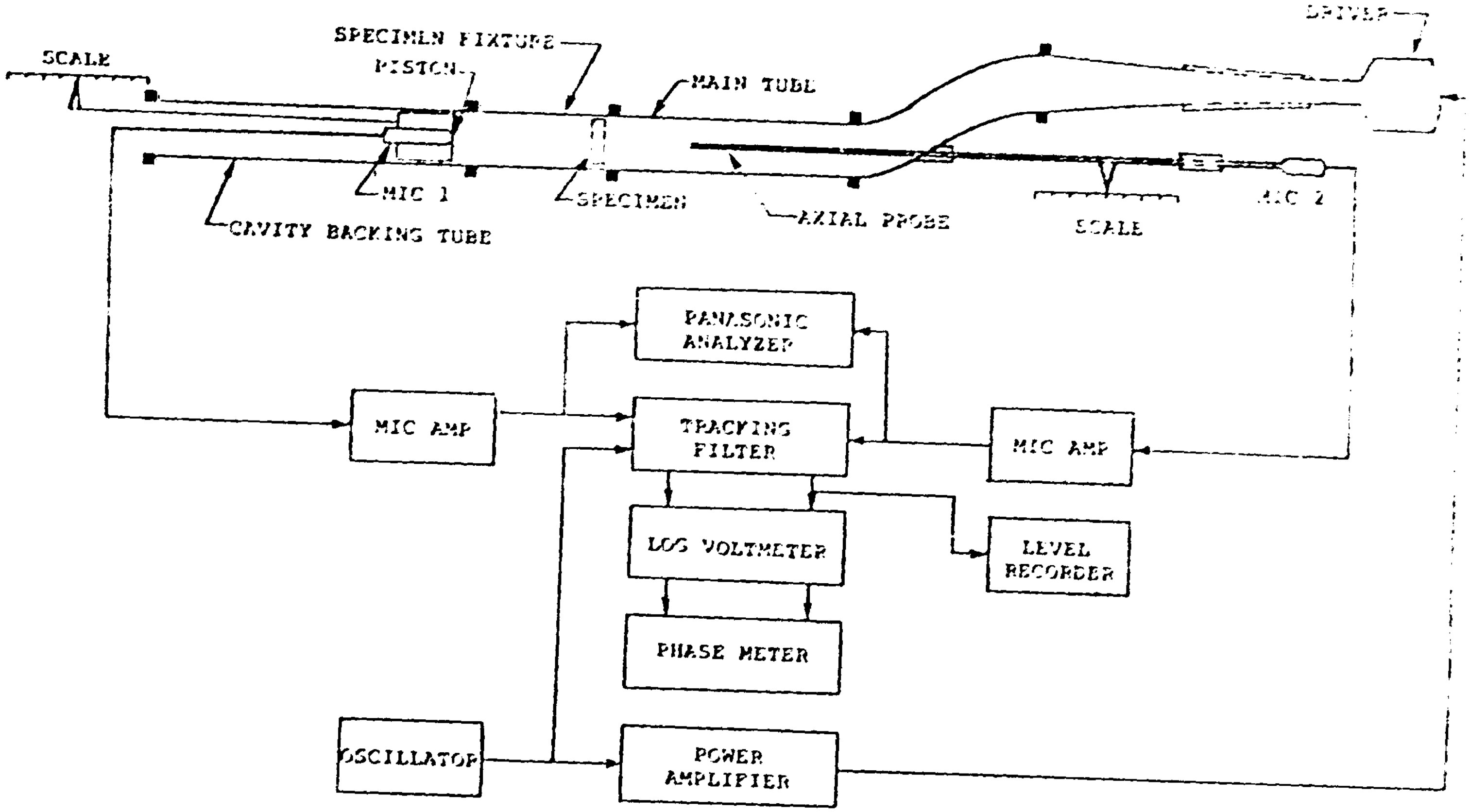

Figure 2. Schematic diagram of impedance tube and instrumentation.

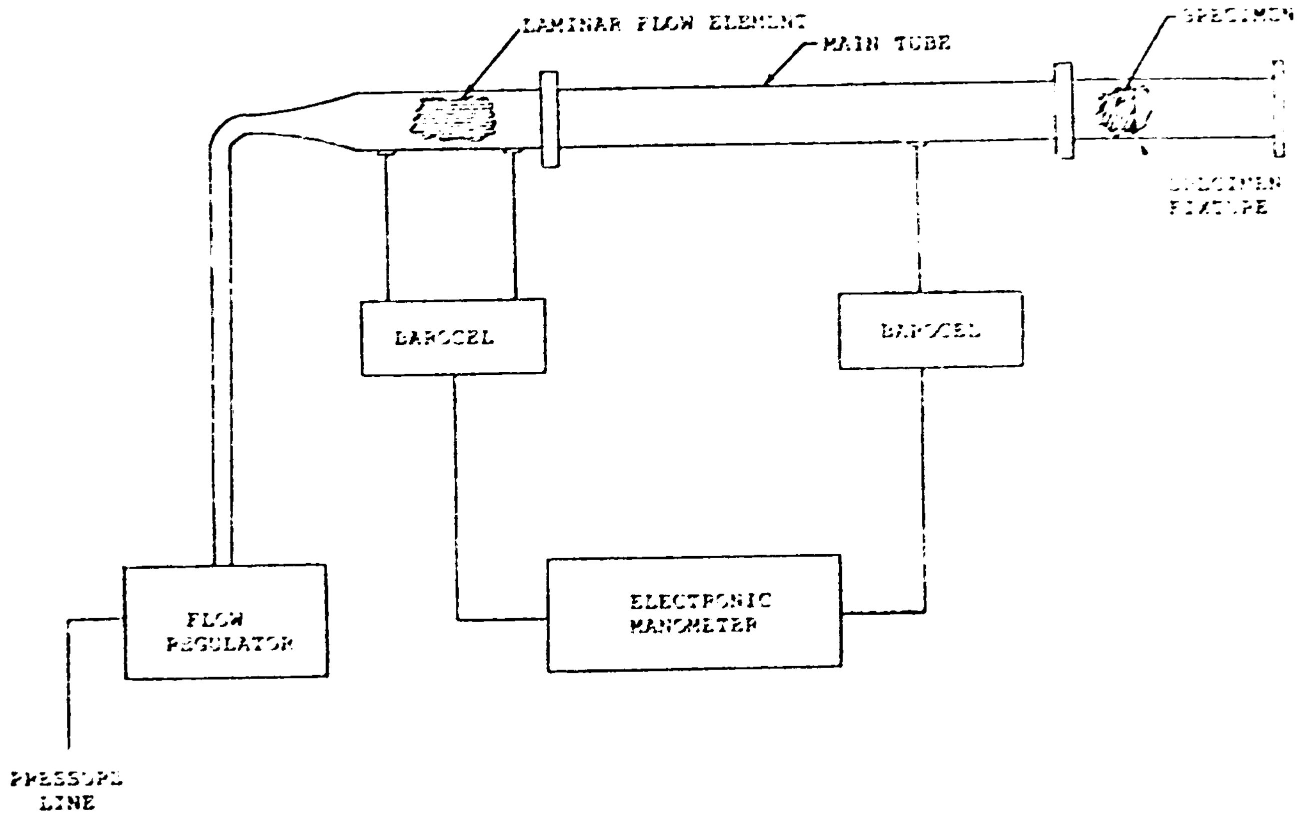

Figure 3. Schematic diagram of flow resistance apparatus and instrumentation.

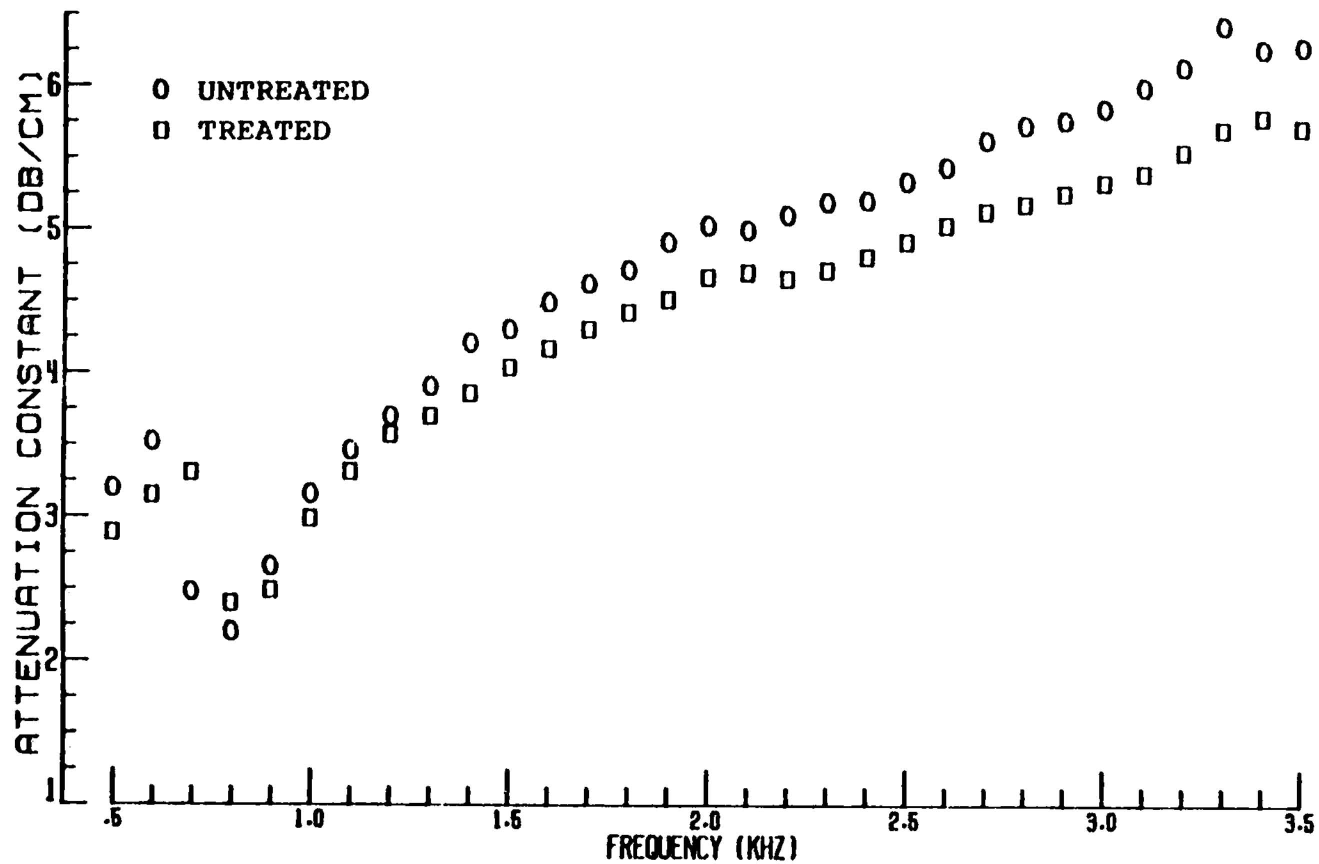

Figure 4. Attenuation constant of Kevlar as a function of frequency.

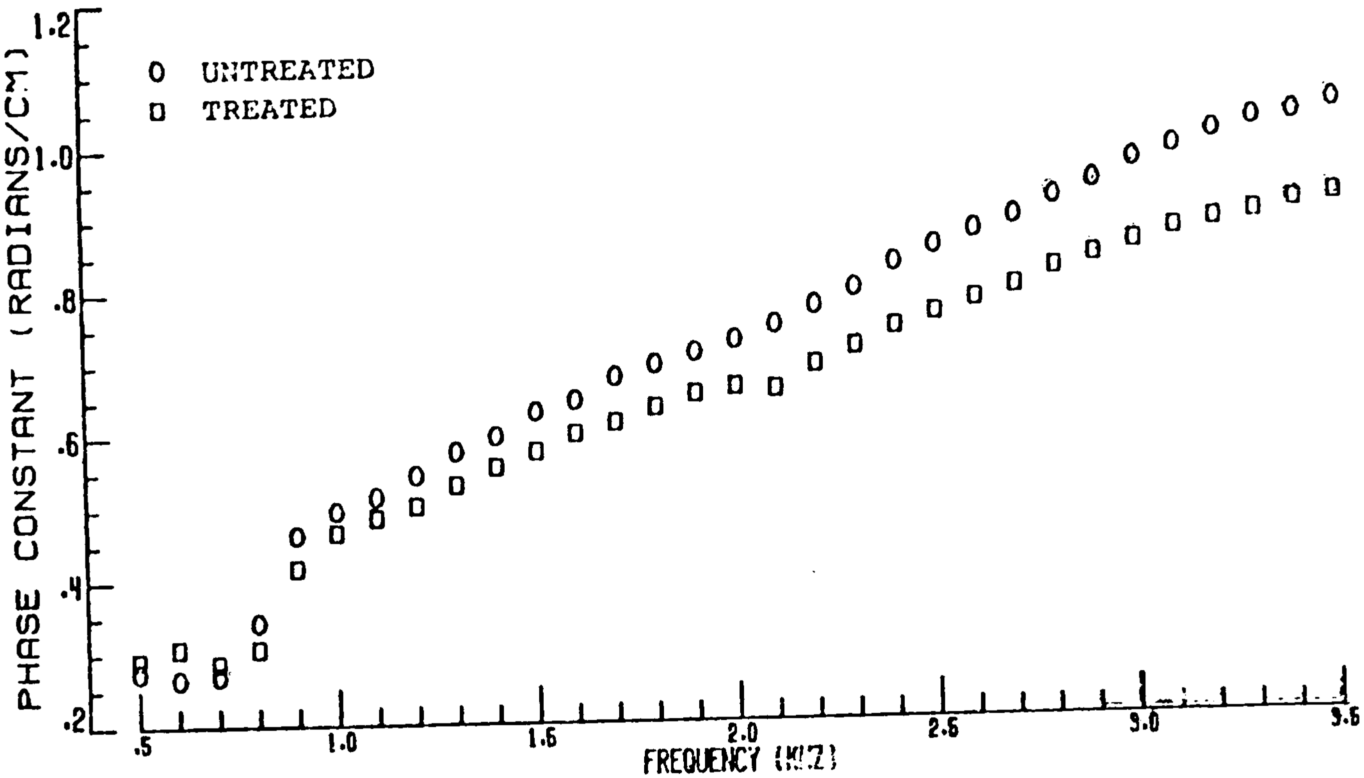

Figure 5. Phase constant of Kevlar as a function of frequency.

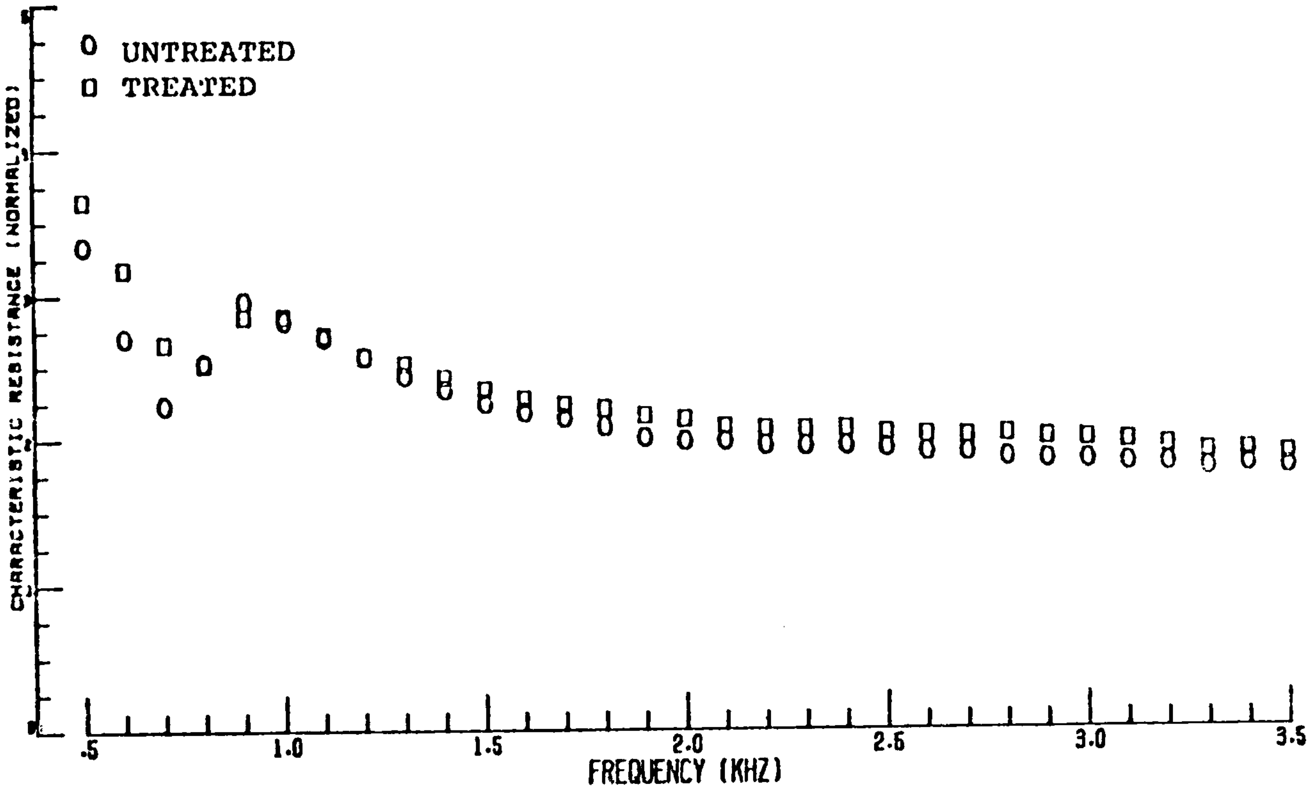

Figure 6. Characteristic resistance of Kevlar as a function of frequency.

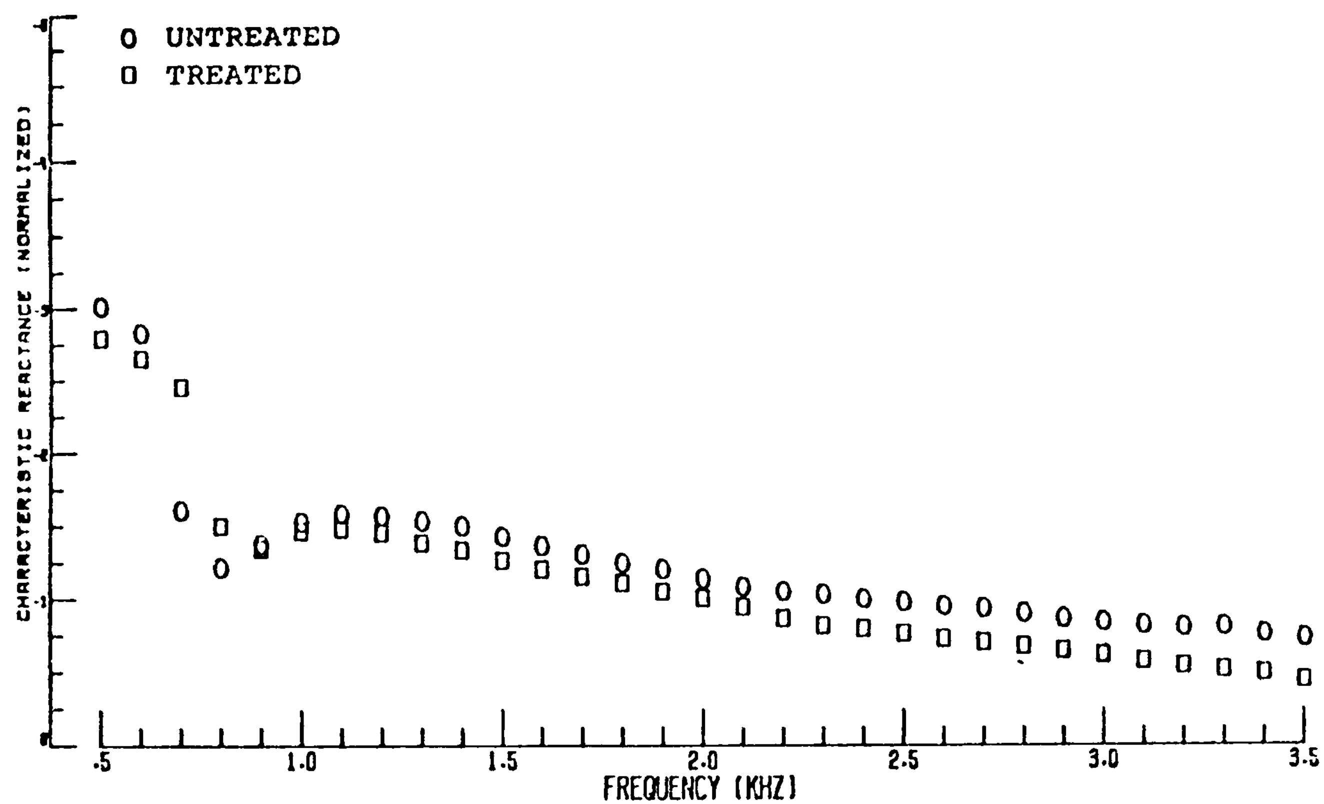

Figure 7. Characteristic reactance of Kevlar as a function of frequency.

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16. Abstract

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